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(71) Applicant(s)
Hewlett Packard Company
(Incorporated in USA - California)
3000 Hanover Street, Palo Alto, California 94303, United States of America

(72) Inventor(s)
Serge L Rudaz

(74) Agent and/or Address for Service
Williams,Powell & Associates
34 Tavistock Street, LONDON, WC2E 7PB, United Kingdom

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EP 0716457 A2

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(54) Nitride LED

(57) N-type doping in III-V-nitride semiconductor compounds i.e. GaN-based compounds such as GaN, AlGaN, AlInN, InGaN, or AlGaInN, is optimized to improve N-contact electrical resistance, carrier injection, forward voltage, and recombination characteristics without inducing cracking of the device layers by constructing the N-type layer of sub-layers (16A, 16B) such that an N-type sub-layer is provided for each desired characteristic or property and selecting the thickness of each sub-layer to avoid material cracking: the higher the required doping, the smaller the corresponding thickness. The buffer layer (14) of a light emitting device (LED) has three sub-layers. The first sub-layer (16A) is lightly doped to avoid cracking and is grown to the desired thickness for good material quality. The second sub-layer (16B) is heavily doped to provide good N-contact and electrical resistivity characteristics and is kept correspondingly as thin as necessary to avoid material cracking. The third sub-layer (16C) is doped to the desired level to provide optimum carrier injection and pair recombination in the active layer of the device.

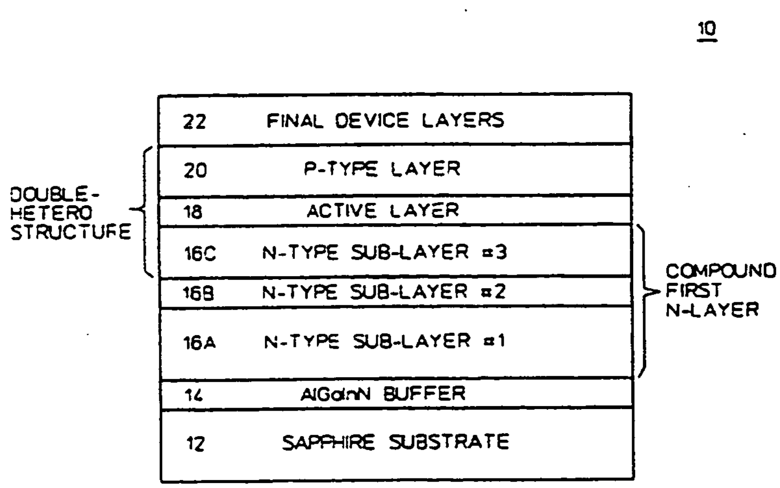

Figure 1

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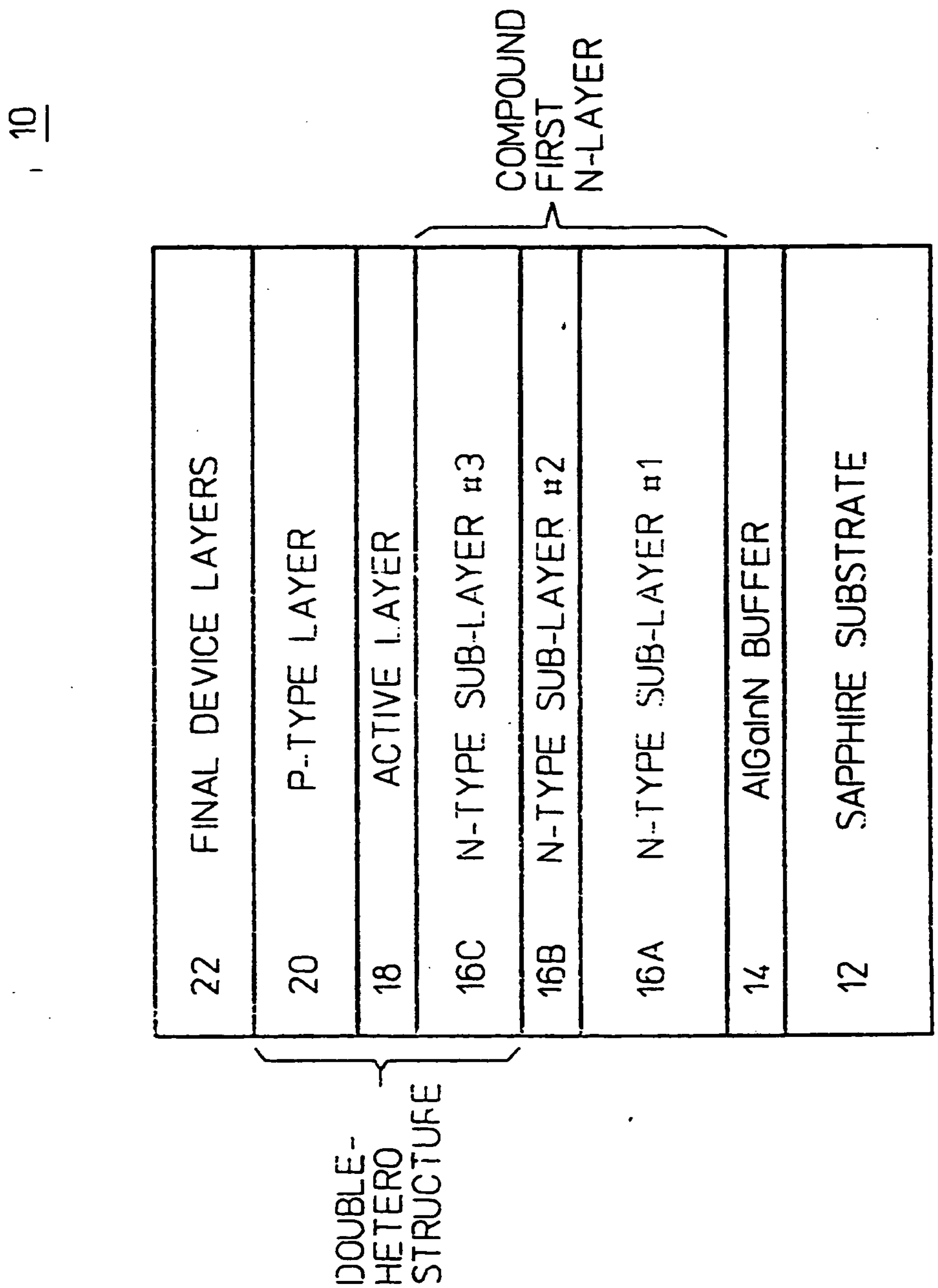

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COMPOUND FIRST N-LAYER
22 FINAL DEVICE LAYERS
20 P-TYPE LAYER
18 ACTIVE LAYER
16C N-TYPE SUB-LAYER #3
16B N-TYPE SUB-LAYER #2
16A N-TYPE SUB-LAYER #1
14 AlGaInN BUFFER
12 SAPPHIRE SUBSTRATE
DOUBLE-HETERO STRUCTURE

Figure 1

30

40	FORM BUFFER LAYER OVER SUBSTRATE
50	GROW FIRST N-TYPE SUB-LAYER FOR MATERIAL QUALITY (LOWER DOPING, HIGHER THICKNESS)
60	GROW SECOND N-TYPE SUB-LAYER FOR FOR LOW ELECTRICAL RESISTIVITY AND LOW FORWARD VOLTAGE
70	GROW THIRD N-TYPE SUB-LAYER FOR OPTIMUM CARRIER INJECTION/RECOMBINATION AND LIGHT OUTPUT EFFICIENCY
80	FINISH GROWING LED STRUCTURE

Figure 2

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DOPED SEMICONDUCTOR DEVICES

This invention relates to doped semiconductor devices and in particular to the manufacture of gallium-nitride-based devices. More particularly, the invention is directed towards improving the electrical characteristics as well as the light extraction from gallium-nitride-based light emitting devices without incurring material cracks.

Gallium nitride (GaN)-based compounds have wavelength emissions in the green and blue range of visible light and in the near ultra-violet. Because single crystals of gallium nitride are difficult to grow, commercial GaN substrates are unavailable for the epitaxial growth of GaN-based devices. Currently, most GaN-based light emitting devices (LEDs) are epitaxially grown on a sapphire substrate. The difference in lattice constants and in coefficients of thermal expansion between the sapphire substrate and the GaN-based semiconductors makes it difficult to grow a high quality GaN-based epitaxial layer on the sapphire substrate. Furthermore, a highly conductive P-type GaN semiconductor is nearly impossible to obtain due to combinations of high N-type background concentration and low P-type doping activity. Although the basic heterojunction device concepts have been well understood for many years, these difficulties stymied the development of efficient heterojunction lasers and LEDs emitting green or blue light using an $(Al_xGa_{1-x})_yIn_{1-y}N$ (where $0 \le x \le 1$ and $0 \le y \le 1$) material system (heretofore known as AlGaInN).

During the late 1980s, a highly efficient GaN-based LED became a possibility when researchers discovered the importance of growing GaN or AlN buffer layers at low temperatures. Growing a buffer layer on a sapphire substrate at low temperatures improves the morphology of the subsequently grown AlGaInN layer and reduces the N-type background concentration of the AlGaInN materials. This coupled with post-growth thermal annealing or low energy electron beam irradiation to activate the P-type dopants has made growing conductive P-type GaN easier. These technological advances have greatly accelerated the progress in device development of an AlGaInN material system for optoelectronics and other applications.

Recent advances have allowed the growth of good AlGaInN devices on substrates other than sapphire, although these substrates are not yet widely available commercially. New buffer material systems other than AlGaInN (such as zinc oxide ZnO) have also been used. Thick AlGaInN single crystals have been grown on silicon and sapphire wafers by hydride vapor phase epitaxy (HVPE) and subsequently used as substrates for AlGaInN device growth. Silicon carbide (SiC), ZnO, bulk GaN, and various garnets have also been used with success. These substrates usually have much better lattice matching to GaN than sapphire and may not require a preliminary buffer layer to obtain good quality device layers. However, in all cases, whether or not a buffer layer is used and depending on the desired device properties (such as color of the emitted light), there still is a significant difference in lattice constants between the substrate and some of the AlGaInN device layers. This comes about because the lattice constant (as well as the electrical and optical properties) of a $(Al_xGa_{1-x})_yIn_{1-y}N$ layer changes with the molar ratios x and y. As a result, material quality issues are encountered similar to the ones with the growth on sapphire.

Generally, growing a buffer layer over the substrate allows good quality N-type and P-type device layers to be grown. But, when the N-doping of an AlGaInN device layer is increased above 2E18 cm^{-3} as measured by Hall effect (for instance for a Si-doped GaN layer within an LED), some of the device layers exhibit severe

cracking when the highly-doped layer exceeds a few micrometers (μms) in thickness because of the large lattice mismatch and thermal expansion coefficient difference with the substrate. Prior art devices minimize cracking by using a thin layer when high doping is required or by lowering the doping when a thick layer is required. As the doping of a device layer increases, the thickness of the layer decreases to avoid cracking. However, a thick first device layer (typically 3-4 μms) is needed to maintain material quality while the high dopings can improve the electrical and optical performance of the device by lowering the N-contact resistance, the forward voltage, and the bulk resistance within the N-doped layers. Material cracking impacts device performance severely and affects reliability.

An LED having increased N-type doping in one or more device layers while having good material quality is a highly desirable feature for optimizing the electrical characteristics (e.g. forward voltage and series resistance). It would be further beneficial if the dopings could be further optimized to provide for improved carrier injection and pair recombination to improve light output efficiency.

N-type doping in III-V-nitride semiconductor compounds, *i.e.* GaN-based compounds such as GaN, AlGaN, AlInN, InGaN, or AlGaInN, can be optimized to improve N-contact electrical resistance, turn-on and forward voltages, minority carrier injection and recombination characteristics without inducing cracking of the device layers. -This is achieved by fabricating a compound N-type device layer that has several sub-layers. For each desired electrical characteristic or property, there is a corresponding N-type doped sub-layer. The thickness of each sub-layer is carefully selected to avoid material cracking: the higher the required doping, the smaller the corresponding thickness.

For a light emitting device (LED), a compound N-type device layer has three sub-layers. The doping level of each sub-layer has been selected to optimize a selected physical property. The first sub-layer is undoped or lightly doped to avoid cracking and is grown to the desired thickness for good material quality. The second sub-layer is heavily doped to provide good N-contact, forward voltage, and electrical resistivity characteristics and is kept correspondingly as thin as necessary to avoid material cracking. The third sub-layer is doped to the desired level to provide optimum carrier injection and pair recombination in the active layer of the device: its doping is typically lower than the second sub-layer's, and correspondingly its thickness can be greater if so desired.

Figure 1 illustrates a device of the present invention, where an N-type, compound layer is grown first.

Figure 2 illustrates a fabrication process flow chart for the device shown in Figure 1.

Figure 1 illustrates an N-type LED 10 of the present invention. An $(Al_xGa_{1-x})_yIn_{1-y}N$ buffer layer 14 is positioned on a substrate 12, such as a sapphire substrate. A compound device layer 16 of N-type AlGaInN is positioned over the AlGaInN buffer layer 14. A D(ouble)-H(etero) structure is formed from a device sub-layer 16C, and from an active layer 18 and a single or composite P-type layer 20 of AlGaInN compound-semiconductor grown over the compound device layer 16.

The compound device layer 16 has three sub-layers 16A, 16B, and 16C of N-doped AlGaInN material, such as GaN:Si. Each sub-layer has a unique doping level. The first sub-layer 16A is lightly doped to avoid cracking and is grown to the desired thickness for good material quality. The doping level of the first sub-layer 16A may be N_d= 2E18 cm^{-3} (as measured by Hall effect) and the associated thickness may be 3.5μm. The second sub-layer 16B is heavily doped to provide good N-contact, forward voltage, and electrical resistivity characteristics. The doping level of the second sub-layer 16B may be N_d = 8E18 cm^{-3} (as measured by Hall effect) and the associated thickness may be kept at or below 0.4μm to avoid cracking. The optional third sub-layer 16C is doped to the desired level to provide optimum carrier injection and pair recombination in the active layer 18 of the device. The doping level of the third sub-layer 16C may be N_d = 2E18 cm^{-3} (as measured by Hall effect). The third sub-layer provides independent doping control for optimum current injection and recombination in light emitting double-hetero-structure devices, such as blue and green light emitting diodes (LEDs) and lasers (such as edge-emitting lasers and Vertical-Cavity-Surface-Emitting-LaserS).

Figure 2 illustrates a process flow chart 30 for the device shown in Figure 1. In step 40, the buffer layer is formed directly on the sapphire substrate. In step 50, the first N-type device sub-layer is formed directly on the buffer layer at growth temperatures that range from 300 C to 1500 C, while the thickness of the first sub-

layer may vary between 1.0 μm to 300 μm in thickness. In step 60, the second sub-layer is formed over the first sub-layer at comparable growth temperatures, while the thickness of the second sub-layer is typically 0.05 μm to 1.0 μm in thickness, with an N-type doping above 2E18 cm^{-3} (as measured by Hall effect): the doping level is selected to optimize the electrical characteristics of the device and the thickness is kept thin enough to avoid cracking: the higher the sub-layer doping, the smaller the sub-layer thickness. In step 70, the optional third sub-layer is formed over the second sub-layer to a selected doping and thickness. The doping and thickness are selected to improve current injection and optical recombination. In step 80, the remaining device layers are formed over the composite device layer at a growth temperature that ranges from 300C to 1500C.

The sub-layers may be grown using one of many available techniques such as organometallic vapor phase epitaxy (OMVPE) (also called metal-organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), gas source MBE (GSPMBE), or hydride vapor phase epitaxy (HVPE). The $(Al_xGa_{1-x})_yIn_{1-y}N$ sub-layers may or may not have the same chemical composition (i.e., same x and y molar ratios). The composition and/or doping of the sub-layers may change abruptly from one sub-layer to another, or may instead be smoothly graded over a finite thickness, or may be graded over the entire thickness of the sub-layers.

Although a compound N-type layer having three sub-layers has been illustrated to improve the following characteristics; N-contact electrical resistance, forward voltage, current injection, and radiative recombination, without inducing cracking of the device layers, additional N-type sub-layers may be added such that the composition, thickness, and doping level of each layer accommodates a desired electrical characteristic or physical property for the device. The compound structure is further extendible to alleviate cracking problems occurring in other, highly N-doped or P-doped layers sequences in semiconductor devices

CLAIMS

1. A device comprising:

a substrate; and

a compound device layer of $(Al_xGa_{1-x})_yIn_{1-y}N$, positioned over the substrate, including a first and second sub-layer, wherein each sub-layer has an associated composition, thickness, and doping level selected for a corresponding physical property;

wherein the composition and thickness associated with each of the sub-layers is adjusted to minimize material cracking such that the higher the doping of the sub-layer, the thinner the thickness of the corresponding sub-layer.

2. A device as defined in claim 1, further comprising:

a buffer layer interposing the substrate and the compound device layer.

3. A device as defined in claim 1 or 2, the compound device layer further including a third sub-layer, having an associated doping level, positioned over the second sub-layer, wherein the associated doping level of the third sub-layer is selected to provide the physical property of optimum carrier injection and pair recombination in the active layer for light emission.

4. A device as defined in claim 1 or 2, wherein the associated doping level of the first sub-layer is selected to provide the physical property of good material quality and the associated doping level of the second sub-layer is selected to provide the physical property of low electrical resistivity and low device forward voltage.

5. A device as defined in claim 4, wherein the associated doping level of the second sub-layer is heavily doped as compared to the associated doping level of the first sub-layer.

6. A device as defined in claim 5, wherein the compound device layer has a graded doping from the first to the second sub-layer.

7. A device as defined in claim 6, wherein the compound device layer has a graded composition from the first to the second sub-layer.

8. A device as defined in claim 5, wherein the compound device layer has a graded composition from the first to the second sub-layer.

9. A device as defined in claim 5, wherein the ratio of the associated doping levels of the first and second sub-layers is between 1 and 100000.

10. A device as defined in claim 4, the compound device layer further including a third sub-layer, having an associated doping level, positioned over the second sub-layer, wherein the associated doping level of the third sub-layer is selected to provide the physical property of optimum carrier injection and pair recombination in the active layer for light emission.

11. A device as defined in any preceding claim, wherein the compound device layer consists of P-type $(Al_xGa_{1-x})_yIn_{1-y}N$ material.

12. A device as defined in claim 1, wherein the compound device layer consists of N-type $(Al_xGa_{1-x})_yIn_{1-y}N$ material.

13. A device as defined in claim 12, wherein the associated doping level of the first sub-layer is selected to provide the physical property of good material quality and the associated doping level of the second sub-layer is selected to provide the physical property of low electrical resistivity and low device forward voltage.

14. A device as defined in claim 13, wherein the associated doping level of the second sub-layer is heavily doped as compared to the associated doping level

of the first sub-layer.

15. A device as defined in claim 14, wherein the compound device layer has a graded doping from the first to the second sub-layer.

16. A device as defined in claim 14, wherein the compound device layer has a graded composition from the first to the second sub-layer.

17. A device as defined in claim 14, wherein the ratio of the associated doping levels of the first and second sub-layers is between 1 and 10000.

18. A device as defined in claim 13, the compound device layer further including a third sub-layer, having an associated doping level, positioned over the second sub-layer, wherein the associated doping level of the third sub-layer is selected to provide the physical property of optimum carrier injection and pair recombination in the active layer for light emission.

19. A device as defined in claim 18, wherein the associated doping level of the second sub-layer is heavily doped as compared to the associated doping level of the first sub-layer.

20. A device as defined in claim 19, further comprising:
a buffer layer interposing the substrate and the compound device layer.

21. A device as defined in claim 20, wherein the ratio of the associated doping levels of the first and second sub-layers is between 1 and 10000.

22. A device substantially as herein described with reference to the accompanying drawings.

23. A method of manufacturing a semiconductor device substantially as herein described with reference to the accompanying drawings.

The Patent Office

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Application No: GB 9718697.7
Claims searched: 1-23

Examiner: SJ Morgan
Date of search: 13 November 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1K(KEAX,KKB)

Int Cl (Ed.6): H01L; H01S

Other: Online:WPI,JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	EP 0 716 457 A2 (NICHIA) See whole document.	1-5 & 9-14

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